Forest Research Report No. 154

Bioclimatic Analysis of Declining Aspen Stands in Northeastern Ontario

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Bioclimatic Analysis of Declining Aspen Stands in Northeastern Ontario

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Abstract

In 2000-2001, aspen (*Populus tremuloides* Michx.) decline was observed over large areas of northeastern Ontario. We analyzed the bioclimatic characteristics of the affected areas and suggest potential causes of the decline. The bioclimatic characteristics analyzed include forest tent caterpillar (*Malacosoma disstria* Hbn.) defoliation and drought history; forest composition, age, and structure; and soil quality. The decline areas experienced unusually frequent defoliation by forest tent caterpillar in the 10 years prior to the decline: 80% of the decline area has been defoliated more than 3 years since 1989. The spatial similarity between areas of high frequency of defoliation and areas of decline suggests a strong relationship between these factors. According to the Drought Code, used in this analysis to assess soil moisture in the decline areas, northeastern Ontario experienced significant drought in 1998. The combined effect of repeated defoliation and moisture-related stress could have caused the decline. In addition, most of the declining aspen stands are mature or overmature. This characteristic, combined with poor soil quality, could have precipitated the decline.

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We thank the Forest Health group, Anthony Hopkin, and Gordon Howse of the Canadian Forest Service for providing the aspen decline survey and the forest tent caterpillar data. We also thank OMNR's Forest Fire Management Section for providing the climate data, and OMNR's Ecological Land Classification group for access to their computers and databases. Finally, we thank Gordon King, Gordon Kayahara, Brian Fox, and Taylor Scarr of OMNR for their helpful comments.

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Introduction

Trembling aspen (*Populus tremuloides* Michx.) is the most common deciduous species in Ontario's boreal forest (OMNR 1996). Its range extends from the Quebec border in the east to the Manitoba border in the west and from the United States border up to Hudson Bay (Davidson et al. 1988). On relatively dry sites, aspen is generally associated with balsam poplar *(Populus balsamifera* L.), white birch *(Betula papyrifera* Marsh.*)*, and jack pine *(Pinus banksiana* Lamb.). On wetter sites, balsam fir (*Abies balsamea* L.), white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* Mill.), and white birch are common associates. In Ontario's boreal forest, 14% of the total forest area is occupied by the poplar working group (consisting of trembling aspen stands, pure or in association with balsam poplar) (OMNR 1996).

Recently, trembling aspen dieback and mortality, hereafter referred to as *aspen decline*, have been observed over extensive areas of the Clay Belt of northeastern Ontario. Several bioclimatic factors could explain this decline.

Drought is often considered to be the main climatic cause of decline, because trembling aspen loses water through transpiration more rapidly than many other temperate zone tree species (Davidson et al. 1988) and thus needs an adequate supply of water to grow. Drought has also been described as a potential cause for decreased aspen productivity (Hogg 1994, Hogg and Hurdle 1995), stem growth reduction, and crown dieback (Hogg and Schwarz 1999). Growing degree days and summer frost index were found not to be significantly related to aspen growth, but other particular climatic events such as late winter thaw followed by severe spring frost could contribute to dieback (Hogg and Schwarz 1999).

Similarly, soil moisture is the most important soil characteristic for aspen growth and survival. The capacity of soil to retain moisture is controlled by texture, porosity, drainage, and water table depth. The best aspen growth occurs on fresh to moist, well-drained sites such as sandy loams with some organic matter content (Sims et al. 1990). Growth is generally poorer on sandy sites because of low moisture and nutrient content (Fowells 1965). On clay sites, poor aeration limits growth. In the Clay Belt, aspen is associated with nutrient-rich clays and silts such as those found in morainal deposits, deep glacio-fluvial deposits, and lacustrine landforms (Miller 1996). Site quality also has an effect. Locally, stands may sustain heavy mortality on nutrient-poor sites during drought years (Barter and Cameron 1955, Churchill et al. 1964, Duncan and Hodson 1958, Ghent 1958).

A variety of insects have been found on aspen (Davidson and Prentice 1968). Forest tent caterpillar (*Malacosoma disstria* Hbn.), or FTC, is the most spectacular defoliator, and outbreaks occur over very large areas at intervals of about 10 years (Sippell 1962). Outbreaks normally persist for 2 to 3 years. However, heavy defoliation has been recorded for 6 consecutive years in the International Falls area in Minnesota (Witter et al. 1972), for 7 years in Alberta (Shepherd and Brown 1971), and for more than 10 successive years in Minnesota's Cloquet Valley (Millers et al. 1989). Various studies have established that several consecutive years of defoliation can reduce growth (Brandt 1995, Duncan and Hodson 1958, Hogg and Schwarz 1999) and increase stem mortality (Churchill et al. 1964, Hildahl and Campbell 1975).

The role of FTC defoliation in aspen mortality over extensive areas is uncertain. In general, defoliation does not cause significant tree mortality (Duncan and Hodson 1958, Ghent 1958, Hildahl and Reeks 1960, Howse 1981). Complete defoliation of aspen commonly occurs in June, but heavily defoliated trees generally refoliate by the end of July. When the tree survives, growth recovery appears to take 1 growing season after defoliation ceases, even in the most severe cases. Defoliation appears to affect trees differently depending on their dominance status. For example, in stands defoliated for 3 consecutive years, the growth of dominant trees increases the third year after defoliation. Conversely, the long-term (6-10 years) effect of FTC defoliation is increased mortality with increasing defoliation intensity in intermediate, co-dominant, and dominant vigour classes but not in the suppressed class (Churchill et al. 1964). Circumstantial evidence tends to indicate a potential relation when long-term effects of defoliation were observed (Churchill et al. 1964). However, there is

currently no method to positively attribute the mortality to insect defoliation.

Forest composition, structure, and age can also influence aspen's susceptibility to potential causes of mortality. Trembling aspen occurs in pure or mixedwood stands across the range of sites that it occupies in the boreal forest. Typically, aspen stands are even-aged because suckers develop rapidly following major disturbances. Occasionally, an understory of young aspen can develop under a mature or overmature aspen overstory (Peterson 1988). Mueggler (1987) reported that these uneven-aged stands likely form under a stable aspen community as the overstory gradually succumbs to disease or advanced age and new suckers develop in the openings. Forest structure particularly affects the severity of FTC outbreaks: The amount of forest edge per square kilometre is a good predictor of the duration of defoliation (Roland 1993). Specifically, increased forest fragmentation due to exploitation and land conversion from forestry to other uses may exacerbate FTC outbreaks, as FTC's natural enemies are less effective in a fragmented landscape (Roland and Taylor 1997).

The objective of this study was to conduct a range of GIS and descriptive analyses to describe the bioclimatic conditions that characterized the aspen decline observed in northeastern Ontario in 2000 and 2001.

Data and Methods

Our approach to characterizing the bioclimatic conditions in the decline area relies on a sequence involving 3 steps: data gathering, data processing using GIS methods, and descriptive analysis. Data related to the aspen decline and the bioclimatic factors were obtained from various sources. All the spatial data were entered into a geographic information system (GIS) and processed to the same geographical projection. GIS methods were subsequently applied to extract the bioclimatic characteristics of the decline areas. The resulting data set was subjected to descriptive methods to depict the bioclimatic conditions in the decline areas.

Aerial surveys of aspen decline: Aspen decline was first detected in northeastern Ontario in 2000. Preliminary surveys were conducted during the summer of that year. Areas within which decline occurred were digitized from the maps at 1:100,000 used for the surveys. The total decline area was estimated at 174,898 ha. A more exhaustive aerial survey was carried out in the summer of 2001; the total decline area mapped then was 319,469 ha.

Aerial surveys of FTC defoliation: In Ontario, the Canadian Forest Service has conducted extensive aerial surveys of large-scale FTC defoliation since 1948. Mapping is done from a plane by sketching defoliated areas on 1:125,000 or 1:250,000 maps. These maps are then compiled and transferred to smaller-scale maps (e.g., 1:600,000). During the last decade, annual maps of defoliation have been digitized and stored in a GIS. Occasionally, these surveys include other insects potentially harmful to aspen. In 2000 and 2001, defoliation by aspen two leaf-tier (*Enargia decolor* Wlk.) and aspen leaf roller (*Pseudexentera oregonana* Wlsm.) has been recorded west of Hearst (Evans et al. 2000; Scarr, pers. comm., 2001).

Forest age, composition, and structure: Our forest data came from the Forest Resource Inventory (FRI) (OMNR 1996) and the Ontario Land Cover Database (Spectranalysis 1994). The FRI is a stand-level inventory conducted by the Ontario Ministry of Natural Resources. Forest stand characteristics, including tree species composition, stand age, stand height, stocking level, and site productivity class, are derived from interpreted aerial photographs combined with field surveys. The area covered by the inventory is divided into management units, each of which is inventoried approximately every 20 years. In northeastern Ontario, the latest inventory was conducted in 1991 and 1992 in most management units, and between 1988 and 1990 in the rest. Currently, FRI groups trembling aspen and balsam poplar in a common poplar working group because the 2 species are difficult to distinguish using aerial photographs.

The Ontario Land Cover Database is a land cover classification derived from digital, multispectral Landsat Thematic Mapper data recorded between 1986 and 1997. Usually, the land cover was classified automatically using the spectral characteristics of each pixel. However, supervised classification

methods based on extensive field knowledge and interactive editing were also used to map classes that could not be positively identified by their spectral value only (Spectranalysis 1994). Across the province, 28 classes were used to map vegetative and non-vegetative land covers. Among these 28 classes, 9 were useful for our analysis: water bodies, dense deciduous forest, dense coniferous forest, mixed forest mainly deciduous, mixed forest mainly coniferous, sparse coniferous forest, sparse deciduous forest, treed fen-bog, and cleared. Based on the definitions of these 9 classes (OMNR 1999), the coefficients representing forest density, the percentage of coniferous trees, and the percentage of deciduous trees were attributed to each class (Table 1). The Ontario Land Cover Database was used at its original resolution of 25 m and at a resolution of 625 m obtained by aggregation from 25 m. For each block of 625 x 625 m, the forest density and the percentage of deciduous trees were computed averaging 625 pixels at 25 m, using the coefficients in Table 1.

Soil data: These were derived from the Ontario Land Inventory, which is part of the Canada Land Inventory (CLI) program. Between 1965 and 1980, CLI assessed soil capabilities for agriculture, forestry, recreation, and wildlife. Mapping was carried out at 1:50,000 and 1:250,000. We used digital versions of the soil capabilities for forestry at 1:250,000 for our analysis. The soil capabilities for forestry indicate productivity, best species, and growth limitations. Productivity (based on the mean annual growth of optimum species or species groups at rotation) is rated from 1 to 7 in decreasing order of capability. For example, land rated 1 has no important limitations to the growth of commercial trees, whereas land rated 7 has severe limitations that preclude the growth of commercial trees. A low productivity rating (i.e., higher classes close to 7) is generally accompanied by an indication of growth limitations such as excess soil moisture, low fertility, or exposure. The Ontario Land Inventory does not provide soil data for the entire province; in northeastern Ontario, soil information was not available for the westernmost part of the region. However, soil information was available for 88.5% of the total decline area.

Climate data: Drought is often considered the most likely climatic cause of decline (Hogg and Schwarz 1999). However, finding a suitable measure of drought stress can be difficult (Millers et al. 1989). We chose the Drought Code (DC), a component of the Canadian Forest Fire Weather Index, to indicate any water stress that could explain the decline. DC represents the balance between moisture losses due to evaporation and transpiration and gains due to precipitation. By construction, DC is a slow-drying moisture index and, therefore,

Table 1. *Coefficients assigned to the most relevant classes of the Ontario Land Cover Database.*

	Value	Forest density	Deciduous (%)	Coniferous (%)	Cleared (%)
Water	1	0	0	0	1
Deciduous dense	2	1	0.9	0.1	0
Deciduous mixed	3	1	0.65	0.35	0
Deciduous sparse	4	0.35	0.31	0.04	0.65
Coniferous dense	5	1	0.1	0.9	0
Coniferous mixed	6	1	0.35	0.65	0
Coniferous sparse	7	0.35	0.04	0.31	0.65
Treed fed-bog	8	1	0.5	0.5	0
Cleared	9	0	0	0	1

integrates past weather over a relatively long period, usually several weeks (Van Wagner 1970). Typically, DC is used as an indicator of the moisture content of deep organic layers and the availability of water in small streams and swamps (Van Wagner 1987). As a result, it correlates well to the total soil moisture under most weather patterns (McAlpine and Eiber 1985).

Daily Drought Code values for 1963-2001 are available for 3 weather stations located near or in the decline area: Cochrane at the eastern limit, Hearst at the western limit, and Kapuskasing in the middle of the decline area. Because DC is primarily used to assess fire risk, it is calculated only during the fire season, typically between May 1 and the end of August or September. There is usually little variation in the Drought Code among nearby locations unless a particular land feature, such as mountains, affects weather patterns (McAlpine 1990). The absence of such a feature in northeastern Ontario allows us to extend the observations made at the 3 stations to the entire area. Mean daily DC values were calculated for a 30-year period (1963-1992), as well as the 5th and 95th percentiles. Daily DC values for every year between 1994 and 1999 were compared with the 30-year average to detect any unusual drought event during the period prior to the decline.

GIS methods: To build our data set, spatially referenced data of aspen decline and the bioclimatic variables were saved in a GIS and transformed to a common projection, with each variable represented by a layer. Several arithmetic manipulations were performed on each layer.

Results

Aspen decline areas: Decline was extensively mapped during summer 2001. The decline map (Figure 1) reveals that most of the affected areas were located along Highway 11 between 80° W and 85° W. A total of 735 decline areas, ranging from 5.5 to 120,849 ha, were mapped. The largest areas were near Smooth Rock Falls and south of Kapuskasing. The total decline area was 319,449 ha.

One striking characteristic of the spatial distribution of the decline areas was that they tended to be located near the roads. Particularly remarkable was the distribution of the small decline areas along Highway 11 between Smooth Rock

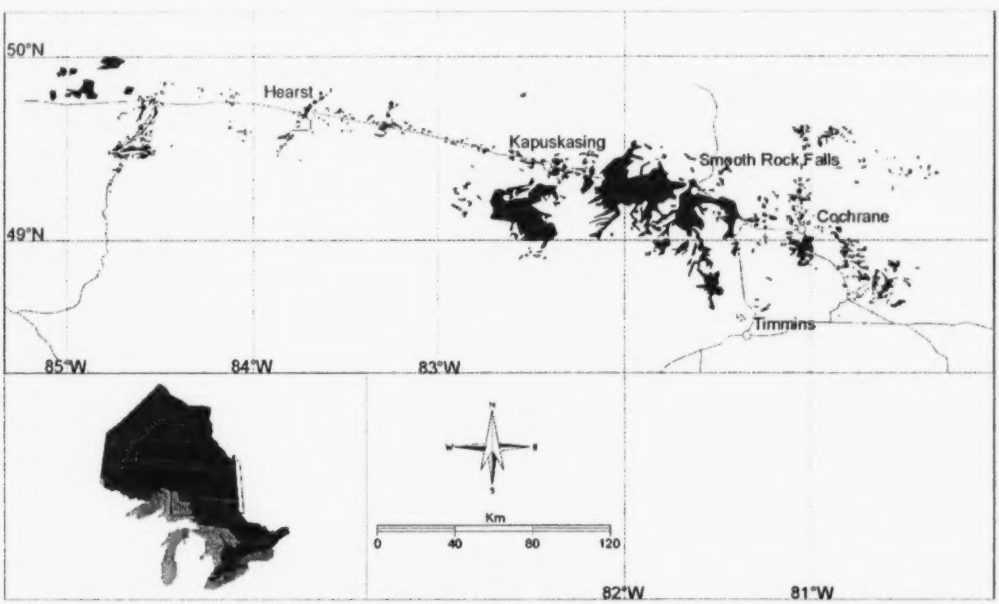

Figure 1. *Aspen decline areas surveyed in 2001 in northeastern Ontario, primary and secondary highways, and location of aspen decline area in Ontario (inset map). For the purpose of our analysis, the boxed area in this inset is referred to as* northeastern Ontario.

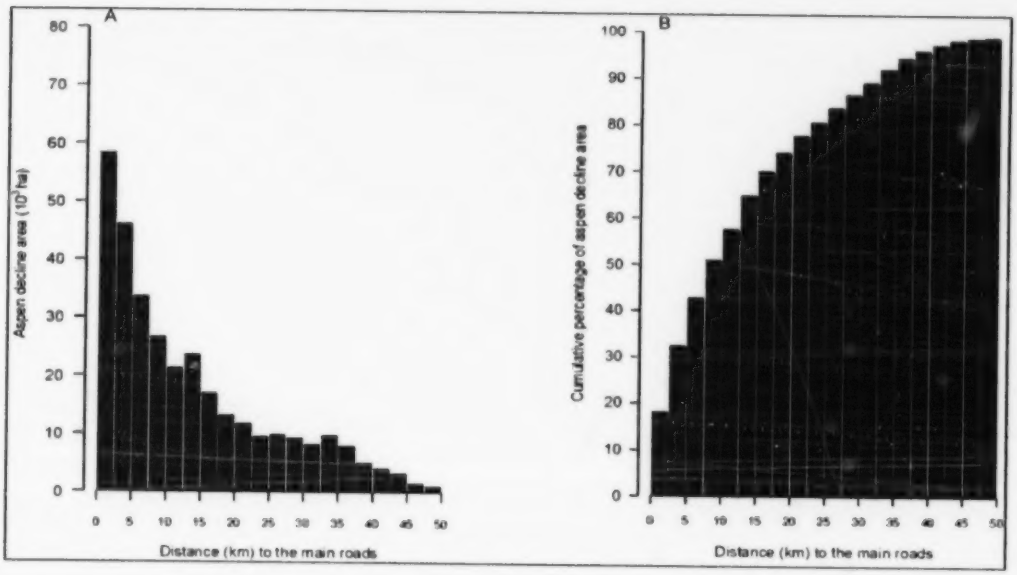
A
Aspen decline area (10^3 ha)
Distance (km) to the main roads
B
Cumulative percentage of aspen decline area
Distance (km) to the main roads

Figure 2. *Distribution and cumulative distribution of the distance between aspen decline areas in 2001 and the closest road.*

Falls and Kapuskasing, along Highway 631, north of Cochrane along Highway 579, and along other secondary roads not represented in Figure 1. The distribution of the distance to the closest primary or secondary highway (Figure 2) shows that the relationship seems to decrease exponentially (Figure 2A). More than 75% of the affected areas were located less than 20 km from the closest highway (Figure 2B).

FTC defoliation: In Ontario, the most recent FTC outbreak peaked in 1992 with 19 million ha of boreal forest moderately to severely defoliated (Fleming et al. 2000). FTC outbreaks are often described as having short durations and occurring at regular intervals (Sippell 1962). However, the pattern of defoliation in northeastern Ontario since the surveys began in 1948 (Figure 3A) is different. Since 1948, northeastern Ontario has experienced 3 outbreaks. The first started in 1949, peaked in 1953, and collapsed in 1957. This outbreak was followed by 14 defoliation-free years (1958-1971), except for 1962 (4,386 ha) and 1965 (31,223 ha). However, since 1972, northeastern Ontario has never been free of defoliation. During this period, 3 peaks of defoliation occurred in 1977, 1992, and 1998. These peaks were separated by periods of low defoliation. The pattern during the last 10 years seems particularly unusual: Defoliation was relatively low at 273,664 ha in 1989, peaked at 6,890,627 ha in 1992, dropped to 208,421 ha in 1994, and increased again to 2,935,900 ha in 1998. If the peaks observed in 1992 and 1998 represented 2 distinct outbreaks, the interval between these outbreaks was unusually short (i.e., only one year in 1994). If the peaks were parts of the same outbreak, this outbreak had an unusually long duration of at least 12 years, since some defoliation occurred in 2000 and 2001.

In the decline areas, the defoliation pattern was similar to the pattern observed in northeastern Ontario as a whole (Figure 3B): Outbreaks in 1953 and 1978 coincided with the defoliation peaks observed in 1953 and 1977 in northeastern Ontario. Since 1989, defoliation has varied from 2% of the total decline area in 1989 to 87% in 1998. During this period, defoliation peaked in 1992 (79% of the total decline area), decreased slightly in 1994 (36%), and then reached a second peak in 1998 (87%). This pattern of 2 pseudo-outbreaks appears similar to the observations at the regional level.

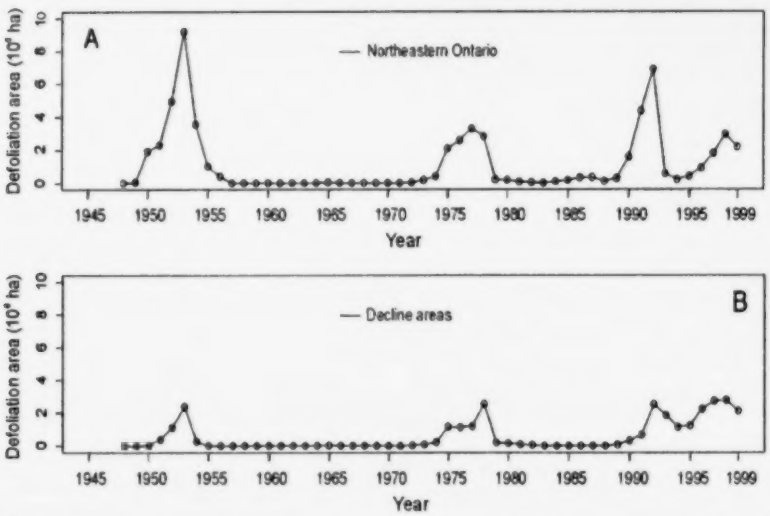

Figure 3. *Defoliation by forest tent caterpillar since 1948 in (A) northeastern Ontario and (B) the decline areas.*

A more detailed analysis of the temporal patterns of FTC defoliation in the decline area between 1989 and 1999 is presented Table 2. For this analysis, time-series of defoliation were filtered to remove unlikely events: one year of defoliation preceded and followed by years without defoliation was converted to no-defoliation, and one year of no-defoliation preceded and followed by years of defoliation was converted to defoliation. Two defoliation periods separated by at least 2 years without defoliation were considered 2 distinct outbreaks. Temporal patterns of defoliation reveal that 64% of the decline area exhibited 2 outbreaks, the second outbreak lasting 3 years in 24% of the total area of decline, and 4 years in 18% of the area. In 28% of the total area of decline, only one outbreak of particularly long duration (8 years) has been recorded. Conversely, only 0.1% of the total area of decline did not experience any defoliation between 1989 and 1999.

The distribution of the defoliation frequency (i.e., number of years of defoliation) since 1989 in the decline areas (Figure 4A) and the distribution of the years since the last defoliation (Figure 4B) reveal some variation in the temporal pattern of defoliation. The distribution of defoliation frequency between 1989 and 1999 (Figure 4A) appears bi-modal with a distribution centred on 5 years and a large class (30% of the total decline area) for 8 years of defoliation. Areas with frequencies between 1 and 6 years generally experienced 1 defoliation peak (Figure 3B) before or after 1994. Areas with

Table 2. *Area distribution (ha) of the duration of first and second outbreaks of forest tent caterpillar in the areas of aspen decline in northeastern Ontario between 1989 and 1999.*

Area of decline (ha)											
Duration of the first outbreak (years)	Duration of the second outbreak (years)										
	0	1	2	3	4	5	6	7	8	9	Total
0	313	1,403	4,974	22,346	25,085	5,920	5,552	5,778	97,204	91,213	169,788
1	1,199	891	1,367	5,126	2,711	2,485	0	0	0	0	13,779
2	14,336	1,221	9,196	43,648	24,047	0	0	0	0	0	92,448
3	15,247	4,042	6,958	4,619	5,906	0	0	0	0	0	36,772
4	1,488	1,417	3,807	143	0	0	0	0	0	0	6,855
Total	32,583	8,973	26,302	75,882	57,748	8,405	5,552	5,778	97,204	1,213	319,642

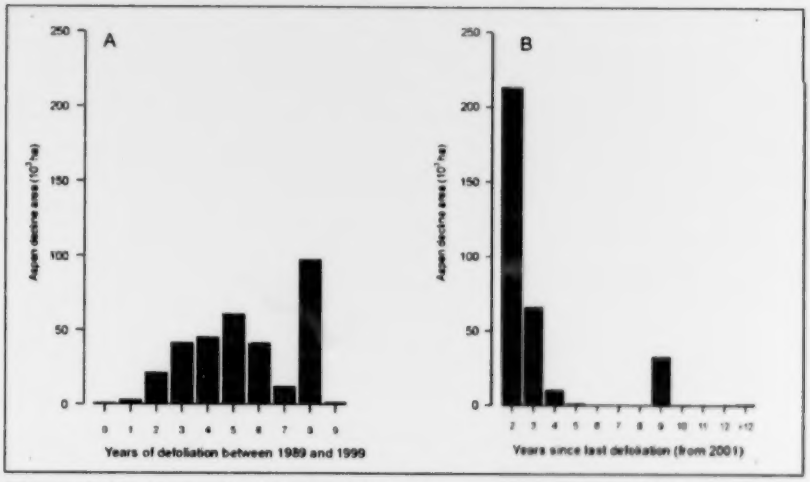

Figure 4. *(A) Years of defoliation in the decline areas between 1989 and 1999, and (B) years since the last defoliation (from 2001).*

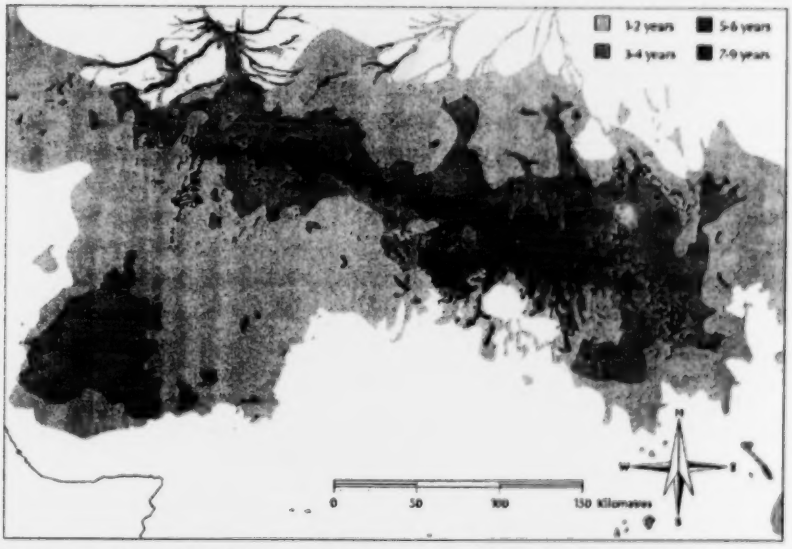

Figure 5. *Years of defoliation by forest tent caterpillar between 1989 and 1999 in northeastern Ontario. The polygons outlined in black are the decline areas observed in 2001. (See Figure 1 for area context.)*

frequencies between 7 and 9 years experienced 2 defoliation peaks. Only 0.1% of the total decline area was never defoliated between 1989 and 1999, whereas 80% was defoliated in more than 3 years.

The map of defoliation frequency (Figure 5) reveals that the patterns of defoliation frequency and the area of decline were remarkably similar. The decline areas near Smooth Rock Falls coincided almost perfectly with the highest classes of defoliation (e.g., 8 and 9 years). The rest of the decline area was found in the second highest classes of defoliation (e.g., 5 and 6 years) south of Kapuskasing and west along Highway 11 and in the class of 3 to 4 years of defoliation in the Cochrane area. On the other hand, almost all the areas with more than 5 years of defoliation showed some decline, and almost no decline was found in areas with less than 3 years of defoliation.

Most of the decline area (67% of the total area) was defoliated 2 years prior to the decline (Figure 4B). The distribution of the time since the last defoliation decreased sharply from 3 to 5 years and

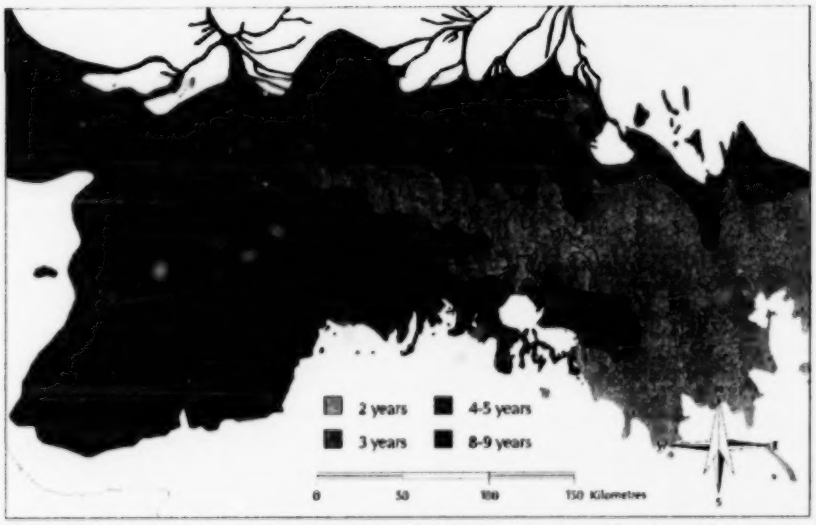

Figure 6. *Years since the last defoliation by forest tent caterpillar in northeastern Ontario in 2001. The polygons outlined in black indicate the decline areas observed in 2001. (See Figure 1 for area context).*

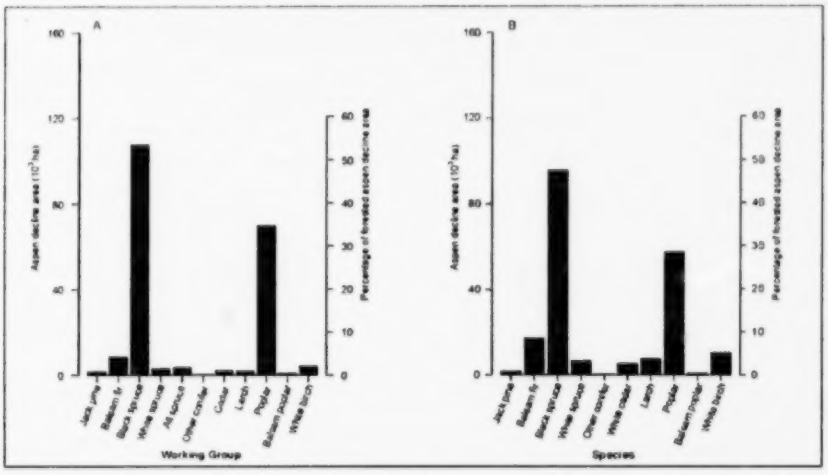

Figure 7. *(A) Distribution of the major working groups in the decline areas and (B) distribution of the major species in the decline areas.*

then increased significantly for 9 years (10% of the total area of decline). The 1-year class (corresponding to a defoliation in 2000) was omitted because FTC defoliation and mortality were difficult to differentiate in the 2000 surveys. The map of the years since the last defoliation (Figure 6) confirms that most of the decline area has been defoliated recently (i.e. in 1999 or 1998). Only the westernmost part of the decline area was last defoliated less recently (9 years).

Forest age, composition, and structure: The distributions of decline areas by working group and by individual species were calculated from the FRI. At the working group level (Figure 7A), 88% of the total decline area was occupied by black spruce (53%) and poplar (35%). At the species level (Figure 7B), black spruce and poplar were still the dominant species (48% and 28% respectively). Balsam fir (8%) and white birch (5%) were the next most common species.

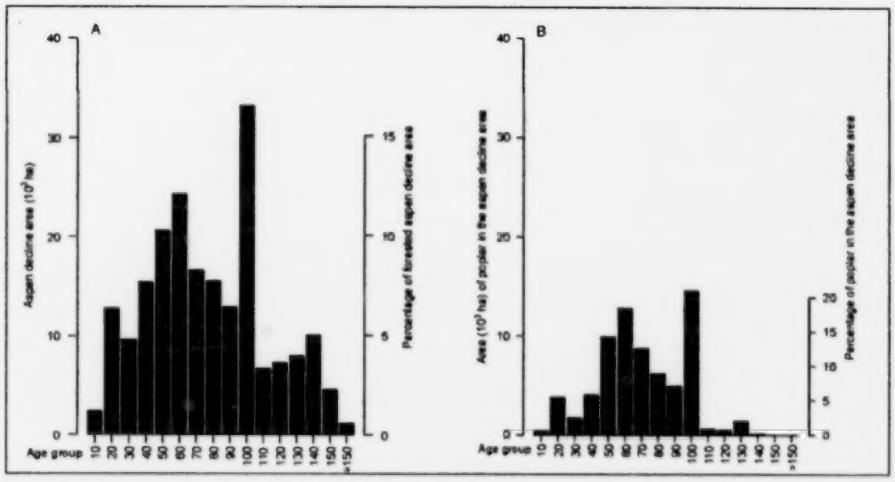

Figure 8. *(A) Age distribution of all the stands in the decline areas and (B) age distribution of the poplar working group in the decline areas.*

The age structure of the forested stands in the decline areas (Figure 8A) was clearly bi-modal, with one mode at 60 years and another mode at 100 years. Stands between 50 and 100 years old made up 61% of the total forested area. Stands over 100 years old occupied 19% of the total forested area. The age distribution of the poplar working group (i.e., stands with mostly trembling aspen and/or balsam poplar), shown in Figure 8B, resembled the distribution of all stands but was more concentrated around the 50- to 100-year age classes. Indeed, stands between 50 and 100 years represented 82% of the total area of the working group, whereas the stands over 100 occupied only 3% of the total area. In both distributions, the first mode corresponds to an age distribution centred around 60 years, which is usual for aspen. In the Clay belt area, aspen reaches maturity between 60 and 90 years, stands start to break up between 90 and 110 years, and thus become decadent after 110 years (King, pers. comm., 2000). The second mode, centred around 100 years, likely indicates that large-scale disturbances occurred in the area at the turn of the 20th century, particularly clearcuts and fires. After a severe disturbance, aspen on fresh to moist soils would generally dominate because of its ability to regenerate profusely.

Forest types in the decline areas were also extracted from the Ontario Land Cover Database at 25 m. The distribution of a classification in sparse and dense forest shows that 71% of the total area was occupied by dense forest (Figure 9A). The distribution of a classification in 9 classes (Figure 9B) reveals that 30% of the total area was classified as mixed coniferous, 16% as mixed deciduous, and 11% as dense coniferous. Mixed coniferous and mixed deciduous represent mostly areas containing black spruce in association with various deciduous species (mostly aspen) in variable proportion. Mixed deciduous forests occur primarily where the bedrock-dominated topography over the Canadian Shield provides suitable habitat for deciduous species. In addition, very old burns and cutover areas would have regenerated as deciduous forests. Dense deciduous forest does not occur extensively in northeastern Ontario (only 10% of the total area), occupying areas of higher elevation, areas around settlements, and areas regenerated after a disturbance.

To assess the forest structure at a different resolution, the land cover database was reclassified from 25 m to 625 m. For each block of 625 x 625 m, the percentage of deciduous trees was computed as the ratio between the number of 25 x 25 m pixels classified as deciduous and the number of 25 x 25 m pixels classified as forested. Forest density at 625 m was also calculated as the percentage of 25 x 25 m pixels classified as forested inside each 625 x 625 m block. The distribution of the percentage of deciduous trees (Figure 10A) appears skewed

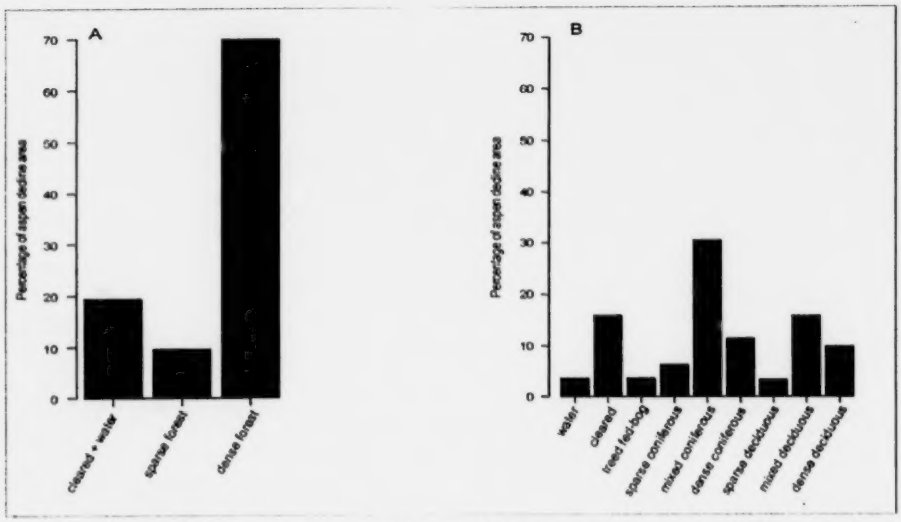

Figure 9. *(A) Distribution of forest type (2 classes) in the decline areas and (B) distribution of forest types (8 classes) in the decline areas using Ontario Land Cover Database at 25 m.*

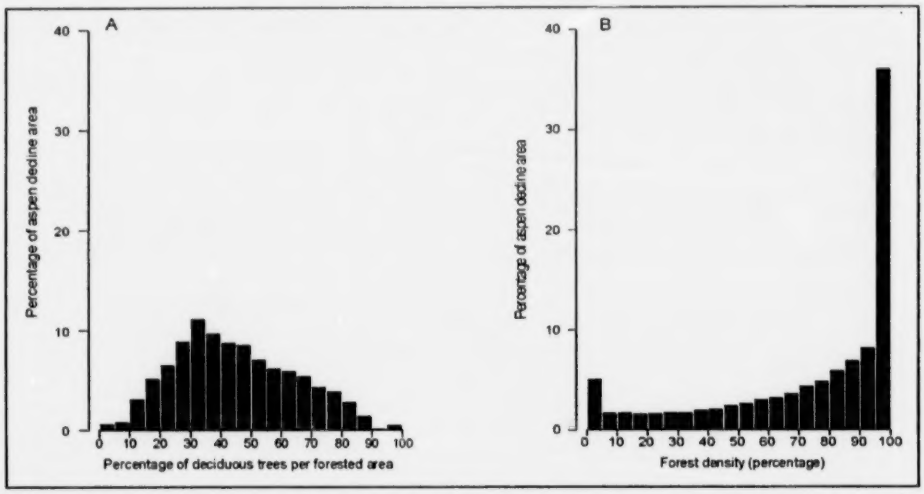

Figure 10. *(A) Distribution of deciduous trees in the decline areas and (B) distribution of forest density in the decline areas using Ontario Land Cover Database reclassified from 25 to 625 m.*

around 30 to 35%, similar to the FRI (Figure 9B), which shows that 36% of the forested areas were covered by deciduous species. The distribution of the forest density (Figure 10B) shows that most of the decline areas had densities between 95 and 100% at 625m.

Soils: The decline areas lie within the northern Clay Belt physiographic region of Ontario. The terrain is a gently sloping and rolling plain of clay till and lacustrine clay, silt, and sand. The soils of most of the decline areas are rated Class 5 (Figure 11A). In northeastern Ontario, this class is associated with deep, moist-to-wet and wet, poorly structured clays, or deep, dry, infertile, silty sands and sands. Class 6 and 7 soils respectively represent 12% and 19% of the total decline area. Class 6 soils are associated with wet mineral clays and some organic soils. Class 7 sites are generally very poorly drained deep organic soils. Only 6% of the decline area had a Class 4 rating, the best in the region. The limiting

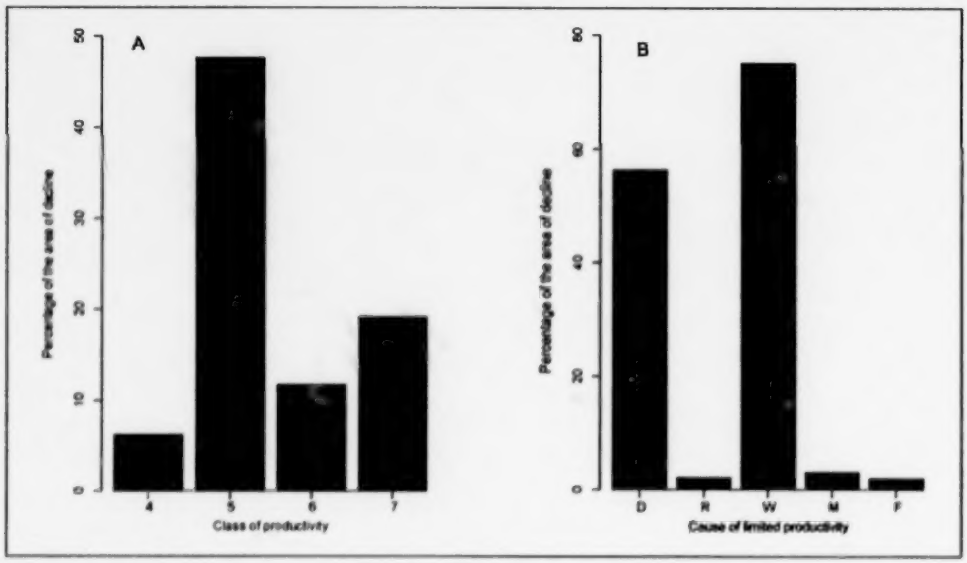

Figure 11. *(A) Distribution of soil productivity classes in the aspen decline areas (classes rank from 1 to 7 in decreasing order of productivity; Class 4 has moderately severe limitations to the growth of commercial forest; Class 7 has severe limitations) and (B) distribution of the primary or secondary causes of low productivity such as physical restriction to rooting by dense or consolidated layers (D), restriction to rooting by bedrock (R), soil moisture excess (W), soil moisture deficiency (M), or low fertility (F).*

factors are excessive soil moisture on 75% of the decline area and physical restriction to rooting on 56% of the total area. Other limiting factors include moisture deficiency (3%), restriction to rooting by bedrock (2%), and low fertility (2%).

Climate: Northeastern Ontario has a fairly humid climate influenced by moist air from low-pressure areas. Precipitation in Kapuskasing averages 861 mm, about half of which falls during the growing season. Temperatures range from a mean of -18.5°C in January to a mean of 17°C in July. Trends in the annual mean Drought Code in Cochrane, Hearst, and Kapuskasing for the period 1963-1999 are shown in Figure 12. These time series did not show any particular periodic behaviour. Regression analysis indicated a significant increase in DC since 1963 in Cochrane ($p < 0.05$), but no significant trends were apparent in Hearst and Kapuskasing during the same period.

For the same 3 locations, daily DC values for 6 years prior to the decline (1994-1999) were compared with the mean daily values, and the 5th and 95th percentiles calculated between 1963 and 1992 (Figures 13, 14, 15). The mean daily DC values exhibited the same general trend in all locations: an increase during spring and summer, followed by a peak in mid- to late August, and a stagnation or decrease in September. A similar trend has been observed across Canada (McAlpine 1990). The mean daily DC in 1994 appeared low in the summer in Hearst (Figure 13) and Kapuskasing (Figure 14), whereas in Cochrane, the DC followed the 30-year average (Figure 15). Persistently low DCs during the summer indicate frequent and abundant precipitation. DC values were higher than average during the second half of the summer of 1995 and in late summer 1996. In 1997, DC was higher than average in the late summer in Hearst and Cochrane but followed the average in Kapuskasing. The most significant pattern occurred in 1998 when DC remained above the 30-year average during the entire fire season in Cochrane and Kapuskasing and from the spring to the middle of July in Hearst. In 1999, DC was higher than average in the late summer in Hearst and Cochrane and fluctuated around the 30-year average in Kapuskasing.

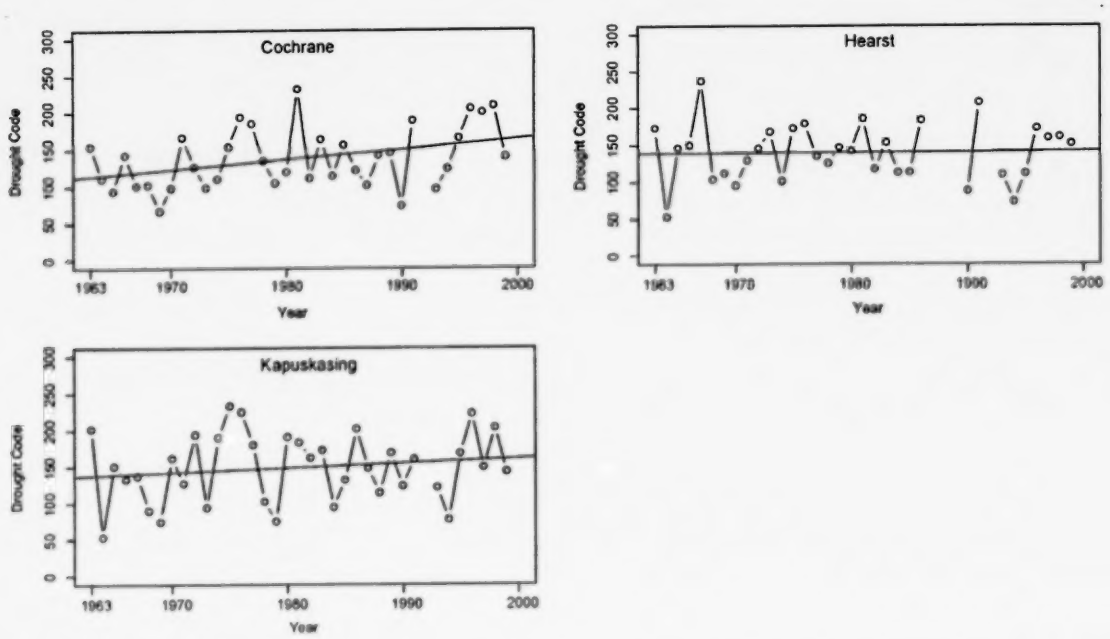

Figure 12. *Annual mean Drought Code and linear trend between 1963 and 1999 for 2 weather stations in northeastern Ontario.*

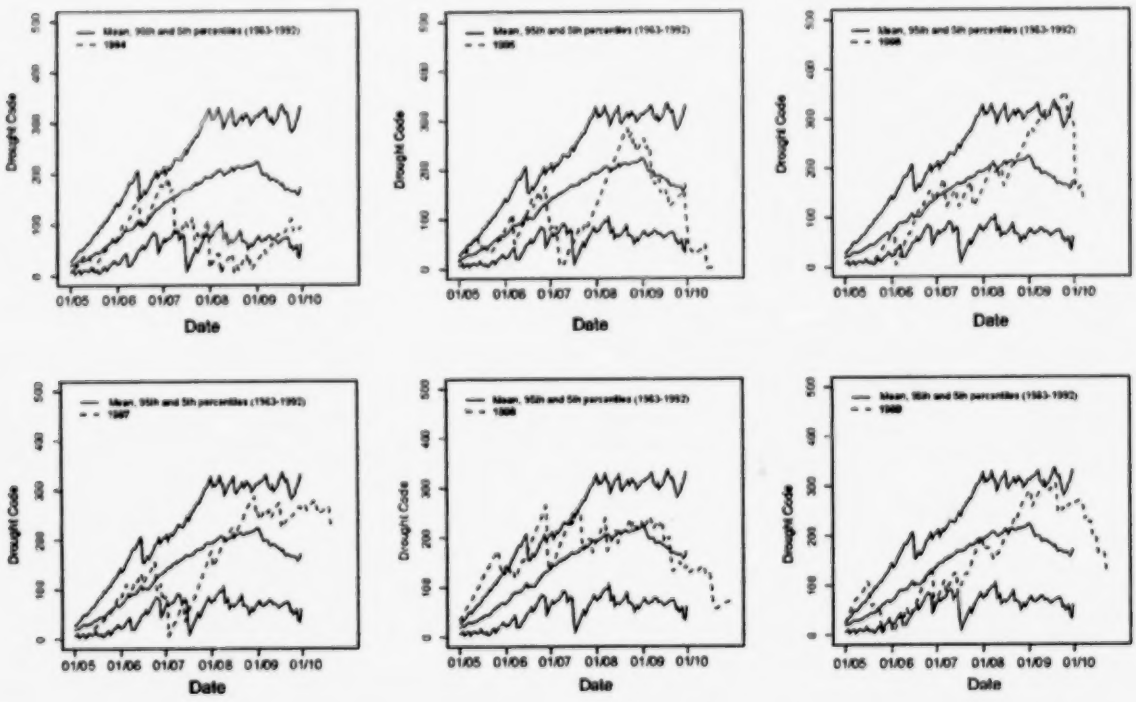

Figure 13. *Seasonal variation of the Drought Code in Hearst (Ontario): annual variations between 1994 and 1999, 30-year average (1963-1992), and 5th and 95th percentiles.*

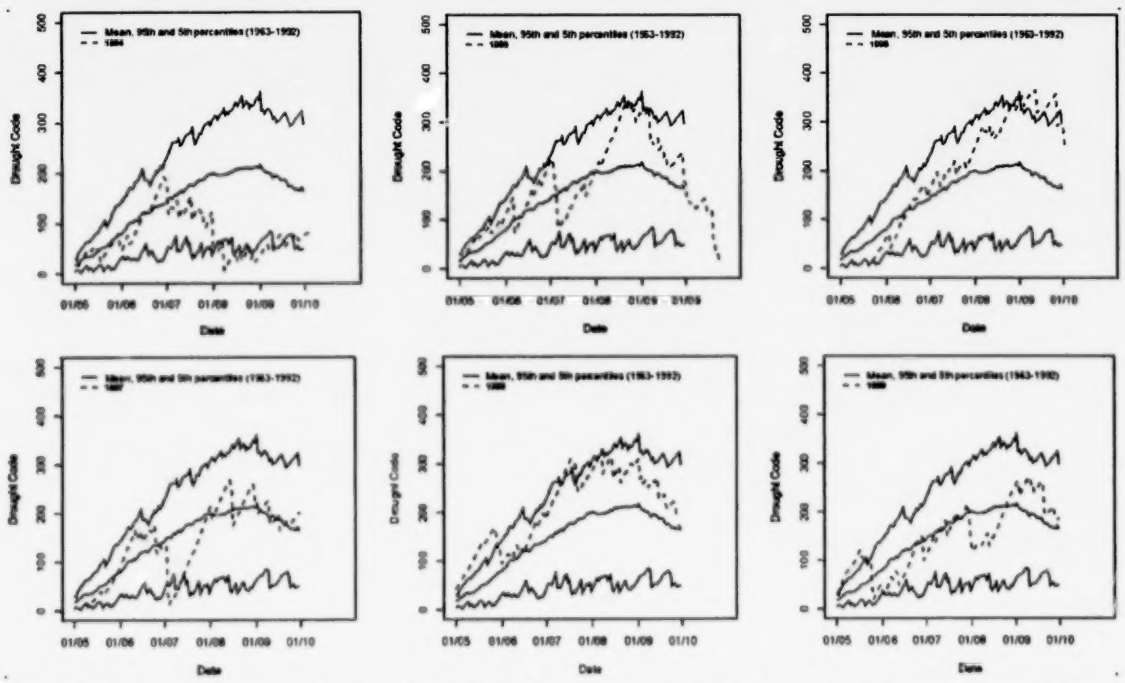

Figure 14. *Seasonal variation of the Drought Code in Kapuskasing (Ontario): annual variations between 1994 and 1999, 30-year average (1963-1992), and 5th and 95th percentiles.*

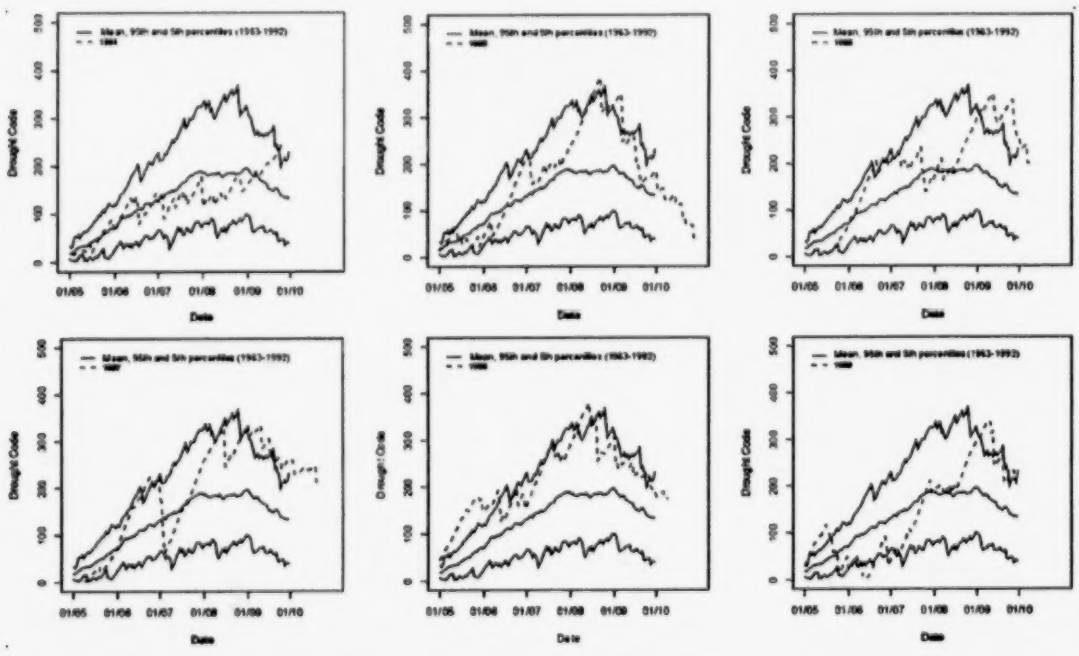

Figure 15. *Seasonal variation of the Drought Code in Cochrane (Ontario): annual variations between 1994 and 1999, 30-year average (1963-1992), and 5th and 95th percentiles.*

Discussion

Many factors act in concert to cause tree mortality (Sinclair 1966). Severe adverse conditions usually provide the decisive stress, while predisposing factors favour the development or intensify the consequences of stress. Decline usually starts with a growth reduction, followed by dieback and death. Recovery can occur, provided that the stress is removed, the damage is not too severe, and secondary agents do not kill the tree. The results of our analysis do not provide a definite identification of the causes of the decline observed in northeastern Ontario in 2000-2001. However, they allow us to suggest a scenario for this decline.

FTC defoliation is suspected to be the primary cause of decline for several reasons. First, the spatial distribution of defoliation frequencies coincides well with the distribution of decline areas: The decline occurred almost exclusively in areas with high defoliation frequencies over the last 10 years (Figure 5); conversely, almost all the areas with highest defoliation frequencies (more than 5 years between 1989 and 1999) were in decline. The similarity between the patterns of decline, particularly in the east-west spread along Highway 11, and the patterns of FTC defoliation frequencies along the same line, is also quite striking. Second, the decline occurred shortly after an unusually long period of defoliation. In most of the decline area, the last defoliation was recorded 2 to3 years before the decline (Figures 4B, 6). In some cases, the last defoliation might even have occurred only 1 year before the decline, i.e., 2000, but this year was not included in our analysis for reasons mentioned earlier. Third, the duration of the last defoliation period in the decline area has been unusually long. Indeed, most of the area has experienced more than 5 years of defoliation during the last 10 years (Figure 4A). Reasons for this extended duration of defoliation since 1989 are unknown. Favourable climate could have played a role, as could have forest composition and fragmentation (Roland 1993). The effect of FTC defoliation on tree mortality is generally negligible (Duncan and Hodson 1958, Hildahl and Reeks 1960, Kulman 1971). However, circumstantial evidence indicates that it could occur when defoliation persists longer than 2 to 3 years (Duncan and Hodson 1958, Ghent 1958, Witter et al. 1975).

Drought conditions in 1998, indicated by high DC values during most of the spring, summer, and fall, lead us to suggest that prior to the decline the forests of northeastern Ontario experienced moisture-related stress, which can reduce growth significantly (Hogg and Schwarz 1999). However, drought severity is not likely to cause major decline unless it is combined with other stresses. Repeated FTC defoliation coupled with dry conditions in the early 1990s have been the most important factors in crown dieback of aspen in Saskatchewan (Hogg and Schwarz 1999). Similarly, in Minnesota, Duncan and Hodson (1958) noticed that tree mortality following an FTC outbreak between 1933 and 1938 coincided with the mid-1930s drought. DC was chosen as an expression of drought because it integrates the fluctuations of temperature and precipitation over a relatively long period (typically several weeks), which seemed appropriate for trees more sensitive to long-term drought than to extremes. Moreover, DC was designed to serve as an index of the water stored in the soil (Turner 1966), an important factor in moisture-related stress. However, DC, or any other expression of drought derived solely from atmospheric measures of temperature and precipitation, does not provide a complete picture of the moisture stress, which is also affected by soil, slope, canopy position, and many other variables. Other methods could be used to measure the drought stress experienced by trees prior to the decline: For example, tree ring width can be used to reconstruct drought events (Fritts 1976); however annual increment can also be altered by defoliators or pathogens. Annual variation in C isotopes discrimination is another indicator of water availability at the tree level (Livingston and Spittlehouse 1993).

Extreme weather events can also cause decline: Hail (Riley 1953) and thaw-freeze events in late winter or early spring (Cox and Malcom 1997) could significantly damage forests. However, these events are often limited to areas smaller than the decline area observed in 2001. Further research is needed to determine how these factors have influenced the current decline.

Finally, soil quality, forest composition, and age distribution could have predisposed aspen stands of northeastern Ontario to decline. Aspen growth and development are strongly influenced by soil conditions. Heavy clays, such as those found in the decline area, do not promote the best growth (Stoeckeler 1948) and likely reduce aspen's resistance to drought and defoliation. In addition, the age-class distribution of the poplar working group reveals that most of the declining aspen is mature to overmature. The 80 to 100-year age classes correspond approximately to the beginning of settlement in this area. Often, settlers would clear the land; but in many cases they would quickly abandon farming because of the difficulty of cultivating the land. Overmaturity is often considered to be a predisposing factor of decline (Millers et al. 1989). Generally, when aspen becomes overmature and decadent, the original stand will disappear within 10 to 20 years. It has been suggested that FTC defoliation could hasten the decadence of overmature aspen (Churchill et al. 1964). However, Ghent (1958) did not find any indication that the period of decadence is shortened by defoliation when trees are severely defoliated for 2 to 3 years. Differences in tree age and defoliation severity could explain these conflicting results.

In conclusion, the bioclimatic characteristics of the declining aspen stands lead us to suggest that an unusually long period of FTC defoliation, combined with drought-related stress, is responsible for the decline observed in 2000-2001. This hypothesis could be verified by analyzing samples collected on dead and living aspen in and around the decline area. In particular, the history of FTC defoliation and moisture stress in individual trees could be retraced using techniques such as the *white growth rings* method (Hogg and Schwarz 1999), and *carbon isotope fractionation* (Livingston and Spittlehouse 1993). Understanding the causes of decline and their interactions is a necessary step towards providing advance warning of future events.

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